Special Issue Honouring Helias A. Udo de Haes: LCA Methodology

Including Human Health Damages due to Road Traffic in Life Cycle Assessment of Dwellings

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Abstract

Goal, Scope and background. Methodologies based on life cycle assessment have been developed to calculate the environmental impact of dwellings. Human health damages due to exposure of occupants to substances and noise emitted by road traffic are not included in these methodologies. In this study, a methodology has been developed to calculate damages to human health of occupants caused by substances and noise emitted by neighbourhood car traffic. The goal of this study is to assess the influence of the location of the dwelling on the health of the occupants, compared to the damage to human health associated with the rest of the life cycle of that dwelling.

Methods. Fate, exposure and human health effects were addressed in the calculation procedure. The methodology takes into account road traffic noise and four hazardous substances emitted by cars. Chemical fate factors were calculated with an outdoor exposure model for traffic pollutants, air entrance rates and indoor intake fractions. Fate factors for noise were based on noise levels generated by traffic. Effect factors for substances were based on unit risk factors and extrapolated dose-effect relationships. Effect factors for noise were based on linear relationships between noise level changes and health effects, while taking into account threshold values for noise levels for negative impacts. Damage factors were calculated on the basis of disability adjusted life years (DALYs). Human health damage scores for changes in traffic situations have been calculated for differences in three traffic scenarios in residential areas and for the Dutch reference dwellings.

Results and Discussion. For the Dutch reference dwelling and the traffic situations considered and taking into account noise, particulate matter (PM_{10}), sulphur dioxide, benzene and benzo[*a*]pyrene, communication disturbances and sleep disturbances due to noise and health effects of PM_{10} appear to be dominant in the total damage to human health of occupants caused by neighbourhood car traffic. A sensitivity analysis has shown that a reduction of the car and truck density and of the distance of the façade of the dwellings to the road axis has the largest positive effect on the human health of the occupants, and that a decrease of speed by traffic impediments has only a marginal or even a negative effect. Differences in overall indoor health damage due to different traffic scenarios may be 1.5 to 2 times higher than the total health damage associated with the dwelling life cycle.

Conclusion. Within the limitations of this study, damages to human health of occupants due to indoor exposure to road traffic noise and pollutants appear to be in the same order of magnitude when compared with damages associated with the life cycle of dwellings. This emphasizes the importance to include the location of dwellings in the life cycle assessment of the dwelling.

Keywords: Benzene; benzo[*a*]pyrene; dwellings; human health damages; indoor exposure; life cycle assessment (LCA); noise; particulate matter (PM_{10}); road; sulphur dioxide; traffic emissions

Introduction

The environmental performance of buildings is an important topic. One of the methodologies to assess this is life cycle assessment (LCA). There are several existing LCA tools for dwellings [1]. The general LCA methodology that these assessments build was developed by Udo de Haes and coworkers [2–4]. One of the shortcomings of current LCA-based tools for buildings is the exclusion of the indoor environment and site-specific or site-dependent factors [1,5,6]. In Dutch legislation, indoor environment is dealt with in the Building Decree, and the effects of the location are dealt with in planning procedures [7,8]. However, the inclusion of the indoor environment and the site-dependency might result in a better fit of the actual environmental impacts with the environmental impact of dwellings predicted by LCA tools [6]. Potting described an approach for the inclusion of spatial differentiation in LCA by including a few general site-parameters [9]. Nigge incorporated spatial differentiation in the LCA of natural gas vehicles and concluded that this improved the accuracy of the human health damage for areas with low population density and for large cities [10,11]. In a study performed by Meijer et al., a method has been proposed to incorporate the impact of building materials on the indoor environment in LCA of dwellings and the health effects have been compared with the health effects associated with the rest of the dwelling life cycle [12,13]. In this article, we will deal with a site-specific factor: the impact of local road traffic on the indoor environment of dwellings.

Damage to human health due to road traffic is usually included in the LCA of road traffic. However, several dwelling characteristics, like the distance between the road axis and the façade of the dwelling, ventilation characteristics and insulation of the windows and façades, influence the damage to the health of the occupants significantly. This suggests the usefulness of including the health effects of local road traffic in the LCA of dwellings.

The goal of this research is the assessment of the damage of road traffic to the health of the local residents due to indoor exposure in life cycle assessment of dwellings and to compare these with damage to human health associated with the life cycle of the dwelling as calculated by standard LCA procedures [4,14,15]. These health damages are due to exposure to noise and several pollutants originating from road traffic sources. A default noise reduction due to the dwelling itself is included in the calculations. The indoor exposure models used to calculate health damages are based on the Dutch CAR II model (Calculation of Air pollution from Road traffic) for pollutants [16] and on the work of Müller-Wenk for noise [17,18]. In applying these models, the impact of cars and trucks will be considered. The CAR II model has been developed to estimate average exposure to traffic pollutants and provides emission and exposure data for Dutch traffic situations. The pollutants considered in this study are particulate matter with a diameter smaller than 10 µm (PM_{10}), sulphur dioxide (SO_2), benzene and benzo[*a*]pyrene. For these pollutants, emission data were available in the CAR II model [11] and effect factors were available in the Eco-Indicator 99 methodology using the hierarchist perspective as a starting point. The calculation of the fate factors as described in this study is a generic method. When emission data and effect factors are available for additional substances like aromatic hydrocarbons or heavy metals, health damages due to emissions of these substances can be calculated as well.

The method presented in this paper is suitable for dwellings located in cities and villages with no exceptional meteorological conditions and relatively low buildings along the road. Background noise and noise reflection are not taken into account. The pavement is default asphalt and the number of vehicles per hour at the road is the same in both directions.

1 Methodology

1.1 Traffic scenarios

To include the influence of traffic on human health in the life cycle assessment of dwellings, three traffic scenarios *s* were defined in this study: a reference scenario, a scenario with reduced exposure and a scenario with increased exposure. The reference scenario is an average residential area in the Netherlands with no measures taken to reduce traffic density or traffic speed, and an average distance of the façades from the road axis. The scenario with reduced exposure reflects a residential area with measures taken to reduce traffic density (e.g. by stimulating public transport) and traffic speed (e.g. obstacles and speed ramps). The distance of the façades to the road axis is increased by means of larger gardens in front. The scenario with increased exposure reflects a busy town road in a district where houses do not have gardens in front.

The dwelling assessed is the Dutch reference dwelling [14,19]. It is a one-family row house, constructed with concrete floors and walls between houses, façades of bricks and sand-lime bricks and inner walls made of gypsum and sand-lime bricks [14,19]. The dwelling is supposed to be used by three occupants, who spend 50% of their lifetime on the first floor and 30% on the second floor. The duration of the situation is 70 year, which is equal to the average lifetime of dwellings. Average weather conditions for the Netherlands are used in the calculations.

For the three scenarios, assumed parameters for traffic densities for cars and for trucks, average speeds and distances from the road axis to the façade of the dwelling are given in **Table 1**, based on typical situations in Dutch residential areas [20,21]. The average traffic speeds reflect the low average speed as given in the CAR II model for the different speed types [16]. Although measures regarding the dwelling may be taken when traffic impact is high, such as sound insulation, in this study the dwelling itself is left unchanged.

Table 1: Definition of scenarios

Parameter	Unit	Reduced exposure	Reference	Increased exposure
Traffic density cars	vehicles·h^{-1}	50	100	200
Traffic density trucks	vehicles·h^{-1}	1	5	10
Average speed	km·h^{-1}	20	30	40
Speed type[a]	–	d	c	c
Distance road axis-façade	m	10	5	3

[a] For a description of the speed types, see **Table A1** in the appendix

The difference in damage score between two scenarios can be calculated by **Eq. (1)**:

$$DS_t = DS_2 - DS_1 \tag{1}$$

where DS_t is the difference in damage score between scenario 2 and scenario 1 associated with road traffic (DALY); DS_2 is the damage score associated with road traffic for scenario 2 (DALY); and DS_1 is the damage score associated with road traffic for scenario 1 (DALY).

The damage score of a scenario associated with road traffic can be calculated by **Eq. (2)**:

$$DS_s = \sum_x \left(F_{s,x} \cdot \sum_k (E_{x,k} \cdot D_{x,k}) \right) \tag{2}$$

where $F_{s,x}$ is the fate factor for stressor x of scenario s (kg or dB(A)); $E_{x,k}$ is the effect factor for stressor x and human health damage category k (cases·kg^{-1} or cases·dB(A)$^{-1}$); and $D_{x,k}$ is the damage factor for stressor x and human health damage category k (DALY·case^{-1}). The stressors x assessed in this study are noise and pollutants such as particulate matter and benzene.

The differences in human health damages due to differences in traffic exposure were compared with the human health damages associated with the life cycles of the dwellings along the road as calculated by standard LCA procedures [4,14,15]. Human health damages due to indoor exposure to pollutants and radiation emitted from building materials are taken into account as well. The calculation of these damages has been described by Meijer et al. [12,13]: Fate factors have been calculated based on indoor and outdoor intake fractions for organic compounds, dose conversion factors for radon and extrapolation from measurements for gamma radiation. Effect factors have been calculated based on unit risk factors, (extrapolated) effect doses or linear relationship between dose and cancer cases. Damage factors are based on disability adjusted lost years (DALYs).

1.2 Fate factors

1.2.1 Pollutants

For traffic pollutants, the overall fate factor consists of three parts: a partial fate factor representing the emission of the vehicles and the transport of pollutants to the outside façade of the dwelling, a partial fate factor representing transport of pollutants from outside to inside the dwelling and a partial fate factor representing transport of pollutants from their entrance point of the pollutants to the site of adsorption by the occupants of the dwelling. The last two fate factors are different for the different compartments in the dwelling (see **Fig. 1**). This is reflected in **Eq. (3)**:

$$F_{s,x} = N_p \cdot \sum_v \left(N_{v,s} \cdot F_{v,x,rf} \cdot \sum_a (F_{x,fi,a} \cdot F_{x,ii,a}) \right) \tag{3}$$

where $F_{s,x}$ is the fate factor representing the transport of emitted compound x to the occupants of the dwelling in scenario s (kg); N_p is the number of persons living in the dwelling (–); $N_{v,s}$ is the number of vehicles type v per hour in scenario s (vehicle·h^{-1}); $F_{v,x,rf}$ is the partial fate factor representing the transport of emitted compound x from vehicle type v to the façade of the dwelling (kg·m^{-3}·vehicles^{-1}·h); $F_{x,fi,a}$ is the partial fate factor for compound x from the façade of the dwelling to the indoor air of compartment a (m^3); and $F_{x,ii,a}$ is the partial fate factor for compound x from the indoor air in compartment a to the occupants of the dwelling (–).

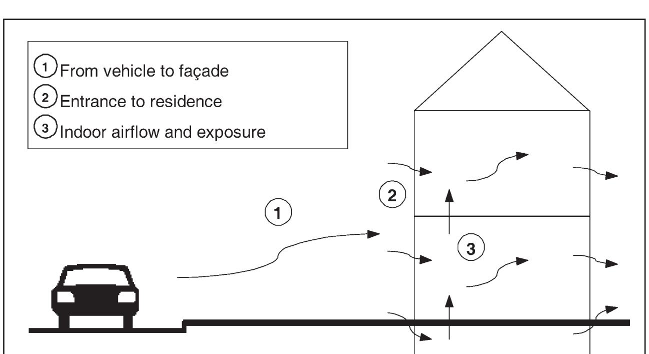

Fig. 1: Transport of pollutants from vehicles to indoor air

The emission of pollutants by vehicles depends on several factors like the vehicle category, fuel, brand, age, speed and road slope. Furthermore, the transport of pollutants from the roadside to the façade of the dwelling are influenced by meteorological factors like wind speed and wind direction. An average emission per vehicle category is used. These averages are different for different countries, because of differences in motor vehicles and fuels. Likewise, a regional meteorological conversion factor is used to represent the influence of the local weather on the transport of pollutants from the road to the façade of the dwelling. The averages used in this study are valid for Dutch traffic situations. The partial fate factor $F_{x,rf}$ for emitted pollutant x from vehicle type v to the façade of the dwelling can be calculated by **Eq. (4)** [16]:

$$F_{v,x,rf} = EF_{v,x} \cdot \theta \cdot CF_t \cdot CF_m \tag{4}$$

where $EF_{v,x}$ is the emission factor of compound x for vehicle category v (kg·m^{-1}·vehicle^{-1}); θ is the dilution factor (m^{-2}); CF_t is the tree factor (-); and CF_m is the regional meteorological conversion factor (h). The tree factor reflects capture of pollutants by the trees along the road. The calculations and values of the parameters in Eq. (4) are given in the appendix.

The partial fate factor $F_{x,fi,a}$ for compound x from the façade of the dwelling to the indoor air in compartment a can be calculated by **Eq. (5)**:

$$F_{x,fi,a} = f_{oa} \cdot CF_{r,f,x,a} \cdot LT_p \tag{5}$$

where f_{oa} is the air entrance rate from the outdoor air to compartment a (m^3·y^{-1}); $CF_{r,f,x,a}$ is the fraction of compound x in the ingoing air that enters compartment a through the façade (–); and LT_p is the duration of the situation (y). The air entrance rate f_{oa} can be calculated using an indoor airflow and exposure model [12]. Air entrance rates for the Dutch reference dwelling [14,19] and fate factors from the façade of the dwelling to the indoor air are given in **Table 2** [12]. It is assumed that all pollutants in the inbound airflow enter the indoor environment [22], so that $CF_{r,f,x,a}$ for each compound x equals 1.

Table 2: Air entrance rates and fate factors for substances from the façade of the dwelling to the indoor air and from the indoor air to the occupants of the dwelling [12]

Compartment *a*	f_{oa}[a] ($m^3 \cdot y^{-1}$)	$F_{x,fi,a}$[b] (m^3)	$F_{x,ii,a}$[c] (–)	
			PM_{10}, BaP[d]	Other substances
Crawlspace	$1.3 \cdot 10^6$	$9.4 \cdot 10^7$	$7.6 \cdot 10^{-6}$	$1.3 \cdot 10^{-5}$
First floor	$2.8 \cdot 10^5$	$2.0 \cdot 10^7$	$1.6 \cdot 10^{-2}$	$2.6 \cdot 10^{-2}$
Second floor	$1.4 \cdot 10^5$	$9{,}8 \cdot 10^6$	$1.9 \cdot 10^{-2}$	$3.1 \cdot 10^{-2}$

[a] Air entrance rate from the outdoor air to compartment *a*
[b] Partial fate factor for compound *x* from the façade of the dwelling to the indoor air in compartment *a*
[c] Partial fate factor for compound x from the indoor air in compartment *a* to the occupants of the dwelling
[d] Benzo[*a*]pyrene

The partial fate factor $F_{x,ii,a}$ for compound x from the indoor air in compartment a to the occupants of the dwelling can be calculated by Eq. (6) [12]:

$$F_{x,ii,a} = CF_{r,i,x,a} \frac{IR}{f_{e,a}} \tag{6}$$

where $CF_{r,i,x,a}$ is the fraction of compound x that is transported from the façade to the occupants in compartment a (–); IR is the inhalation rate of humans ($m^3 \cdot y^{-1}$); and $f_{e,a}$ is the effective outgoing airflow for an emission to compartment a ($m^3 \cdot y^{-1}$). The calculation of $F_{x,ii,a}$ is carried out in an indoor air and exposure model [12]. The fate factors for the Dutch reference dwelling [14,19] are given in Table 2 [12]. The fraction $CF_{r,i,x,a}$ reflects indoor removal of substances by e.g. deposition of particulate matter. This fraction is determined by measured indoor-outdoor concentration ratios and the fraction $CF_{r,f,x,a}$ of the substances. For particulate matter, indoor-outdoor concentration ratios significant lower than 1 have been found [22–25]. In this study, a fraction $CF_{r,i,x,a}$ of 0.6 is assumed for PM_{10} and benzo[*a*]pyrene (which is mostly adsorbed to particulate matter), which reflects precipitation of particulate matter, and 1 for other substances.

1.2.2 Noise

The fate factor for noise can be calculated by **Eq. (7)** [17,18]:

$$F_{s,n} = N_p \cdot LAeq_{f,s} \tag{7}$$

where $F_{s,n}$ is the fate factor for scenario s due to noise (dB(A)); and $LAeq_{f,s}$ is the sound pressure level during daytime at the façade of the house in scenario s (dB(A)).

The noise level is calculated for a scenario rather than on a per-vehicle base because of the non-linear relationship between traffic density and noise level, and because there are threshold values for the noise levels above or under which a change in noise level has no effect on the human health. These thresholds vary per health effect [17] and are give in **Table A5** of the appendix.

The calculation of the sound pressure level is described in the appendix. It is assumed that the sound pressure levels during nighttime are 9 dB(A) lower than the sound pressure levels during daytime [17].

1.3 Effect factors

1.3.1 Pollutants

The methodology to calculate effect factors for pollutants in the indoor air for carcinogenic and non-carcinogenic, non-respiratory effects is described by respectively Crettaz et al. [26] and Pennington et al. [27]. The effect factors can be calculated by **Eq. (8)** [26,27]:

$$E_{x,k} = \frac{\beta_{x,k}}{LT_h \cdot IR} \tag{8}$$

where $\beta_{x,k}$ is the extrapolated slope factor for human health damage category k due to stressor x ($cases \cdot kg^{-1} \cdot m^3$); LT_h is the lifetime of humans (y); and IR is the inhalation rate of humans ($m^3 \cdot y^{-1}$). The lifetime of humans is 70 years and the inhalation rate of humans is 4860 $m^3 \cdot y^{-1}$ [27,28]. The slope factors $\beta_{x,k}$ are given for carcinogenic and non-carcinogenic effects in **Table 3** [12,26,27].

The calculation of the effect factors for respiratory effects of pollutants is described by Hofstetter [28] and in the Eco-Indicator 99 methodology [29]. The hierarchist perspective is applied in this study. The calculation of the effect factors for respiratory effects is similar to the calculation of the effect factors for carcinogenic and non-carcinogenic effects.

The effect factors are given in **Table 3**. In aid of clarity, for substances with respiratory effects only the combined effect and damage factors are given.

1.3.2 Noise

For the calculation of the effect factors for traffic noise, data from epidemiological researches are used [17,30,31]. The examined damage categories are communication disturbances (by day) and sleep disturbances (by night). Müller-

Table 3: Effect and damage factors for traffic noise and pollutants

Stressor	Damage category	$\beta_{x,k}$ [a] ($cases \cdot kg^{-1} \cdot m^3$, $cases \cdot dB(A)^{-1}$)	$E_{x,k}$ [b] ($cases \cdot kg^{-1}$, $cases \cdot dB(A)^{-1}$)	$D_{x,k}$ [c] ($y \cdot case^{-1}$)	$E_{x,k} \cdot D_{x,k}$ ($y \cdot kg^{-1}$, $y \cdot dB(A)^{-1}$)	Literature
Noise	Communication disturbances	0.025	0.025	1.1	0.027	[17,30]
	Sleep disturbances	0.017	0.017	1.3	0.022	[17,30]
PM_{10}	Respiratory	–	–	–	64	[28]
SO_2	Respiratory	–	–	–	0.95	[28]
Benzene	Carcinogenic	$3.0 \cdot 10^3$	$8.8 \cdot 10^{-3}$	17	0.15	[12,29]
	Non-carcinogenic	$7.7 \cdot 10^4$	0.23	0.67	0.15	[12,27]
Benzo[*a*]pyrene	Carcinogenic	$4.4 \cdot 10^7$	130	16	$2.1 \cdot 10^3$	[12,29]
	Non-carcinogenic	n/a[d]	n/a[d]	n/a[d]	–	–

[a] Extrapolated slope factor for human health damage category *k* due to stressor *x*
[b] Effect factor for stressor *x* and human health damage category *k*
[c] Damage factor for stressor *x* and human health damage category *k*
[d] n/a: not available

Wenk [17] obtained the dose-response relationships from the Swiss 'Noise Study '90' [30]. In this study, a linear dose-response relationship between average noise levels and negative impacts has been found. Other studies also found a linear dose-response relationship [32,33]. However, in one field study, an exponential dose-response relationship was found [34]. The average noise levels in residential areas are generally below the noise levels above which a sharp increase in the fraction of people being disturbed. For low noise levels, the dose-response relationship approaches a linear function. Therefore, we assume a linear dose-response relationship between average noise levels and health effects.

The effect factors for communication disturbances and sleep disturbances can be calculated by Eq. (9):

$$E_{n,k} = \beta_{n,k} \tag{9}$$

where $E_{n,k}$ is the effect factor of human health damage category k due to noise (cases·dB(A)$^{-1}$); and $\beta_{n,k}$ is the linear dose-response slope for human health damage category k due to noise (cases·dB(A)$^{-1}$). The dose-response relationships from the Swiss 'Noise Study '90' have been used in this study [30].

The effect factors for noise are given in Table 3.

1.4 Damage factors

The disability adjusted life years (DALY) concept has been developed by the World Health Organisation [35] and has been adjusted for use in LCA [17,18,28].

The damage factor regarding human health is for both pollutants and noise is equal to **Eq. (10)**:

$$D_{x,k} = DALY_{x,k} \tag{10}$$

where $DALY_{x,k}$ is the disability adjusted life years for compound x or noise and for human health damage category k (y·case^{-1}).

The damage factors of pollutants have been calculated by Hofstetter [28] and by Pennington et al. [27]. For communication and sleep disturbances, years living disabled is equal to the duration of the situation, corrected for daytime and night-time exposures, respectively 16 and 8 hours per day, and for the fraction spent inside the dwelling during daytime and night-time, respectively 0.7 and 1. The disability weights and years living disabled are given in the appendix. The damage factors for traffic noise and pollutants are given in Table 3.

1.5 Sensitivity analysis

The scenarios defined in section 1.1 differ between each other in more than one parameter. In order to determine the influence of each parameter on the difference in human health damage score between the scenarios and thus what measures are most effective, a sensitivity analysis has been carried out. The 'reference scenario' is taken as default scenario, one parameter is changed each time and the differences in human health damage score between the default scenario and the default scenario with the changed parameter is calculated. The scenarios assessed in this sensitivity analysis are given in **Table 4**.

2 Results

2.1 Scenarios

Fig. 2 shows the scenario differences in human health damage due to road traffic noise and pollutants per environmental intervention. These differences between scenarios are

Table 4: Definitions of parameters for sensitivity analysis

Changed parameter	Positive	Negative
Traffic density cars	50 vehicles·h^{-1}	200 vehicles·h^{-1}
Traffic density trucks	1 vehicle·h^{-1}	10 vehicles·h^{-1}
Average speed	20 km·h^{-1}	40 km·h^{-1}
Distance road axis-façade	10 m	3 m

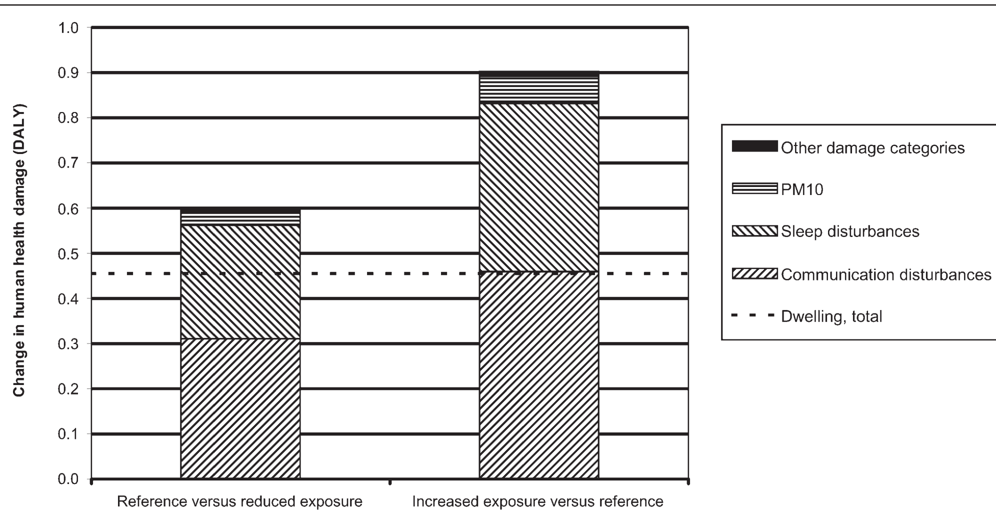

Fig. 2: Change in human health damage due to road traffic noise and pollutants for different scenarios, compared with the damage to human health due to exposure to substances emitted by building materials to the indoor air of the Dutch reference dwelling and associated with the rest of the life cycle of the same dwelling

compared with the damage to human health due to exposure to substances emitted by building materials to indoor air of the Dutch reference dwelling and associated with the rest of the life cycle of the same dwelling [12,13].

The change in human health damage associated with a change from the scenario with increased exposure to the reference scenario is about 1.5 times larger than the change in damage to human health associated with a change from the reference scenario to the scenario with reduced exposure. For all scenarios, human health damage due to communication disturbances accounts for about 50% of the total human health damage; human health damage due to sleep disturbances accounts for about 40% and human health damage due to respiratory effects of PM_{10} for about 5%.

The change in human health damage due to road traffic noise and pollutants is, depending on the scenario, 1.5 to 2 times higher than the total damage to human health due to exposure to substances emitted by building materials to indoor air and the rest of the dwelling life cycle.

2.2 Sensitivity analysis

Fig. 3 shows the results of the sensitivity analysis. It can be concluded that a reduction of the car and truck density and an increase of the distance of the façade of the dwellings to the road axis have the largest positive effect on the human health of the occupants. A decrease of speed by impediments to traffic has only a marginal or even a negative effect on the human health of the occupants. This is caused by a higher emission of traffic pollutants in situations with a stagnating traffic flow due to obstacles and speed ramps. Because of the non-linear behaviour of the noise fate and effect factors, the sum of the individual changes does not equal the total change in human health damage.

3 Discussion

The inclusion of spatial differentiation in life cycle assessment has been discussed by several authors [5,9–11]. Potting described an approach for the inclusion of spatial differentiation in LCA and points out that the use of a site-dependent approach increases the accordance of the impact predicted by LCA and the expected occurrence of actual impacts, without the uncertainty increasing unacceptably [9]. This implies that the LCA of dwellings gives a more complete picture of the total damage to human health occurring in the use phase when local road traffic is taken into account in the scope of the study by means of traffic scenarios as described in this study.

The calculations presented in this study are subject to uncertainties. The traffic scenarios are defined assuming typical conditions for traffic densities, speed and distance between road axis and the façades. When the actual traffic situation differs too much from the situation defined in the traffic scenarios, a new scenario can be defined and the corresponding differences in damage score can be calculated using the method described in this study. A limited number of substances emitted by road traffic have been included in

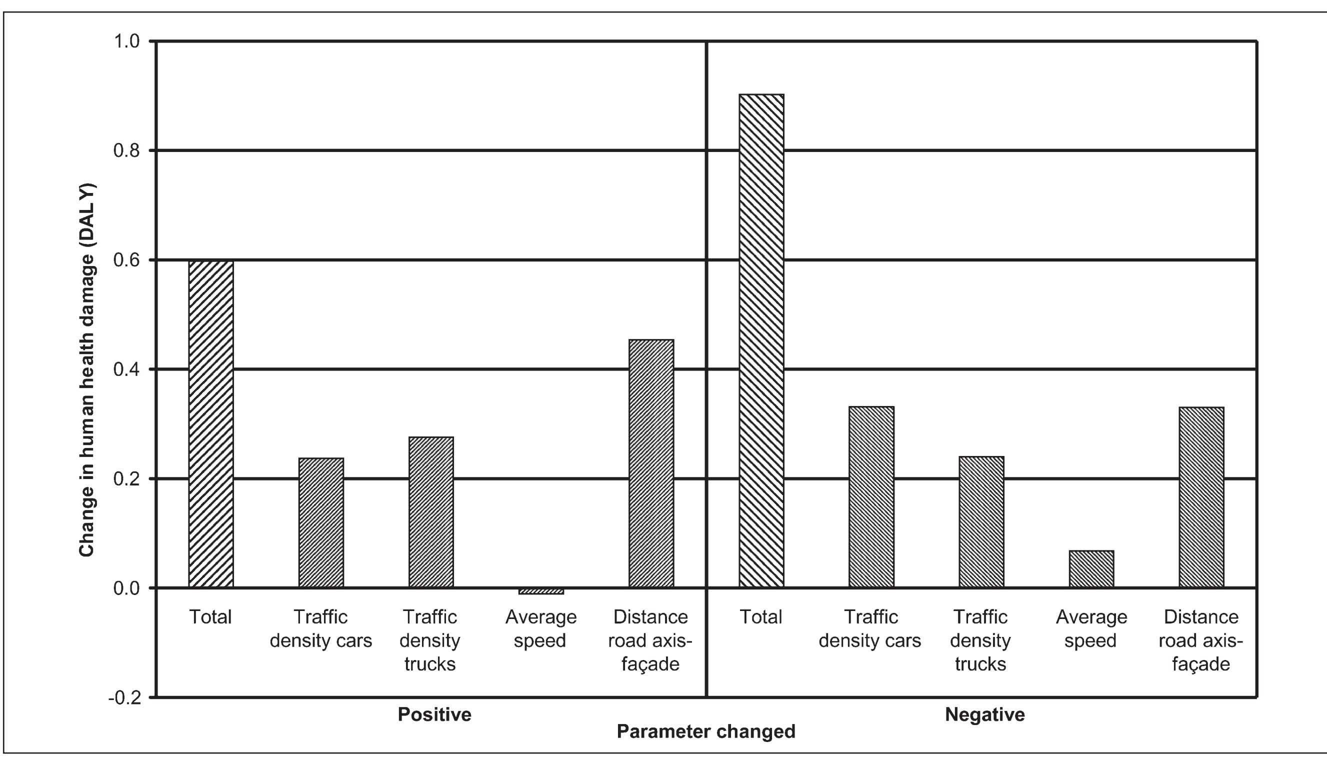

Fig. 3: Change in human health damage due to road traffic noise and pollutants when only one parameter (see Table 4) is changed compared with the change in human health damage when the scenario is changed from typical to positive and from negative to typical

this method. Health damages due to emission of other substances, such as aromatic hydrocarbons or heavy metals, can be calculated using specific emission and effect factors and the generic fate factor calculations presented in this study.

Uncertainties in the fate factor calculation of road traffic pollutants are caused by the use of average emission factors, meteorological conditions, airflow characteristics of the dwelling, fractions of particulate matter that is transported from the façade to the occupants and time fractions spent in the different compartments of the dwelling. It is assumed that all pollutants in the inbound airflow enter the indoor environment, and the effects of sinks other than deposition of particulate matter are not taken into account. This may lead to an overestimation of the human health damage. For noise, the uncertainties in the fate factor calculations lie in the average noise levels caused by road traffic and in the noise characteristics of the dwelling. When the actual parameters differ considerably from the parameters used in this study, new fate factors can be calculated in order to decrease the uncertainties. The health damages for the different traffic scenarios have been calculated for the same reference dwelling. It might be interesting to assess the effects of additional measures such as noise insulation or the use of filters on the damage to human health due to road traffic.

In the effect factors of organic pollutants, sources of uncertainties are the assumed non-threshold behaviour of the dose-response relations and the variability of risk-estimates derived from different sources for the same substance [27,28]. For noise, the uncertainties in the dose-response relationships are the main source of uncertainties in the effect factors [17].

The damage factors are calculated taking account of the duration of a disease or a period of life lost due to premature death, and weighing the severity of disease. As to the matter of duration, the main source of uncertainty is the uncertainty that occurs in the epidemiological data used to determine the years living disabled and years of life lost [27–29]. As to weighing the severity of diseases, it is difficult to determine these due to the subjectivity thereof [27–29,36]. For instance, De Hollander mentions for the severity weight of communication disturbances due to noise values ranging from 0.005 to 0.12, and for the severity weights of sleep disturbances due to noise values ranging from 0.01 to 0.1 [36]. The values given by Müller-Wenk [17] are 0.033 and 0.055 respectively and thus appear to be a reasonable estimate. Uncertainties in the effect and damage factors also apply in the existing LCA methods used for dwellings. With the inclusion of health effects of road traffic, the uncertainties will hence be of the same character and similar order of magnitude.

Due to the uncertainties mentioned above, the damages to human health due to road traffic noise and pollutants are uncertain as well. It might be estimated that these might be one order of magnitude higher or lower due to these uncertainties. However, the conclusion that the change in human health damage due to road traffic noise and pollutants are in the same order of magnitude as the total damage to human health associated with the rest of the dwelling life cycle does not change. Also the sensitivity analysis is not expected to change significantly. Omitting the health effects of traffic will result in a significant underestimation of the overall human health effects associated with living in a particular dwelling.

4 Conclusions

In this paper, damage to human health of local residents due to exposure to noise and pollutants emitted by road traffic has been calculated for three traffic scenarios, based on the disability adjusted life years (DALY) methodology. The differences in human health damage between the different scenarios have been compared with damages to human health associated with the life cycle of dwellings.

The damage scores of a change in traffic situations between the reference scenario and the scenarios with reduced and increased exposure have been calculated for normal Dutch traffic situations in residential areas and for the Dutch reference dwellings. The human health effects of communication disturbances, sleep disturbances and PM_{10} dominate in the total damage to human health of occupants caused by road traffic. A sensitivity analysis showed that a reduction of the car and truck density and an increase of the distance of the façade of the dwellings to the road axis have the largest positive effect on the health of the occupants.

For the Dutch reference dwelling and traffic situations and taking into account noise, particulate matter (PM_{10}), sulphur dioxide, benzene and benzo[*a*]pyrene, differences in overall indoor health damage due to different traffic scenarios may be 1.5 to 2 times higher than the total health damage associated with the rest of the dwelling life cycle. This emphasizes the importance of including the choice of the location of dwellings in the life cycle assessment of the dwelling.

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Appendix: Supporting information

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Appendix: Supporting Information

Fate factors pollutants

The emission factors $EF_{v,x}$ of traffic pollutants differ by speed type. The speed types used in the CAR model are shown in **Table A1**. In **Table A2**, the emission factors of the different vehicle categories per speed type are given for the Dutch situation in 2003 [1].

Table A1: Description of speed types [1]

Speed type	Description	Average speed ($km \cdot h^{-1}$)
a	Motorway	100
b	Road outside built-up area with speed limit of 80 $km \cdot h^{-1}$	44
e	Flowing traffic within built-up area	26
c	Normal traffic within built-up area	19
d	Stagnating traffic within built-up area	13

Table A2: Emission factors ($kg \cdot m^{-1} \cdot vehicle^{-1}$) [1]

Stressor	Cars	Trucks
Speed type a		
PM_{10}	$4.2 \cdot 10^{-8}$	$2.9 \cdot 10^{-7}$
SO_2	$7.0 \cdot 10^{-9}$	$2.8 \cdot 10^{-8}$
Benzene	$7.2 \cdot 10^{-9}$	$6.5 \cdot 10^{-9}$
Benzo[*a*]pyrene	$6.0 \cdot 10^{-13}$	$5.6 \cdot 10^{-12}$
Speed type b		
PM_{10}	$4.9 \cdot 10^{-8}$	$4.3 \cdot 10^{-7}$
SO_2	$7.0 \cdot 10^{-9}$	$3.2 \cdot 10^{-8}$
Benzene	$1.4 \cdot 10^{-8}$	$1.2 \cdot 10^{-8}$
Benzo[*a*]pyrene	$1.1 \cdot 10^{-12}$	$1.0 \cdot 10^{-11}$
Speed type e		
PM_{10}	$7.3 \cdot 10^{-8}$	$5.4 \cdot 10^{-7}$
SO_2	$9.0 \cdot 10^{-9}$	$3.9 \cdot 10^{-8}$
Benzene	$2.5 \cdot 10^{-8}$	$1.7 \cdot 10^{-8}$
Benzo[*a*]pyrene	$2.3 \cdot 10^{-12}$	$1.5 \cdot 10^{-11}$
Speed type c		
PM_{10}	$8.4 \cdot 10^{-8}$	$5.8 \cdot 10^{-7}$
SO_2	$1.0 \cdot 10^{-8}$	$4.2 \cdot 10^{-8}$
Benzene	$2.9 \cdot 10^{-8}$	$1.9 \cdot 10^{-8}$
Benzo[*a*]pyrene	$2.8 \cdot 10^{-12}$	$1.6 \cdot 10^{-11}$
Speed type d		
PM_{10}	$9.7 \cdot 10^{-8}$	$7.5 \cdot 10^{-7}$
SO_2	$1.1 \cdot 10^{-8}$	$5.1 \cdot 10^{-8}$
Benzene	$3.3 \cdot 10^{-8}$	$2.6 \cdot 10^{-8}$
Benzo[*a*]pyrene	$3.2 \cdot 10^{-12}$	$2.3 \cdot 10^{-11}$

The dilution factor θ can be calculated by **Eq. (A1)**:

$$\theta = a \cdot S^2 + b \cdot S + c \qquad (1A)$$

where θ is the dilution factor (m^{-2}); a, b, and c are parameters (respectively m^{-4}, m^{-3} and m^{-2}); and S is the distance from the road axis to the façade of the dwelling (m). The parameters a, b and c for different road types are given in **Table A3**. Road type 1 is not assessed in this study, because it requires another type of calculation of the dilution factor [1]. The default road type used in this study is 3b.

Values for the tree factor CF_t are given in **Table A4**. The default tree factor used in this study is 1. In this study, for the regional meteorological conversion factor CF_m the Dutch 10-year averaged data are used. This yields a value of $3{,}2 \cdot 10^{-4}$ h [1].

Table A4: Description of the tree factors [1]

Tree factor	Description
1	No or some trees
1.25	One or more rows of trees with distance smaller than 15 meter between each tree and gaps between the tree crowns
1.5	The tree crowns touch each other and span at least one third of the road width

Fate factors noise

The average noise level during daytime at 1 meter from the road axis can be calculated by **Eq. (A2)** [2]:

$$LAeq_{r,s} = 10 \cdot \log(10^{0.1 \cdot (Ec + 10 \cdot \log(N_{c,s}))} + 10^{0.1 \cdot (Et + 10 \cdot \log(N_{t,s}))}) \qquad (2A)$$

where $LAeq_{r,s}$ is the average sound pressure level during daytime at 1 meter from the road axis in scenario s (dB(A)); Ec is a car-specific parameter (–); $N_{c,s}$ is the number of cars per hour in scenario s (h^{-1}); Et is a truck-specific parameter (–); and $N_{t,s}$ is the number of trucks per hour in scenario s (h^{-1}).

The car- and truck-specific parameters can be calculated by **Eq. (A3)** and **Eq. (A4)** [2]:

$$Ec = \max\left[(12.8 + 19.5 \cdot \log(V_{c,s})), (45 + 0.8 \cdot (0.5 \cdot i - 2))\right] \qquad (3A)$$

Table A3: Description of road types [1]

Road type	Description	a (m^{-4})	b (m^{-3})	c (m^{-2})
1[a]	Road through open terrain, occasionally buildings or trees within 100 meter of road	–	–	–
2	Roads other than road types 3a, 3b and 4	$3.1 \cdot 10^{-4}$	$-1.8 \cdot 10^{-2}$	0.33
3a	Buildings at both sides; distance axis-façade between 1.5 and 3 times height of buildings	$3.3 \cdot 10^{-4}$	$-2.1 \cdot 10^{-2}$	0.39
3b	Buildings at both sides; distance axis-façade smaller than 1.5 times height of buildings	$4.9 \cdot 10^{-4}$	$-3.1 \cdot 10^{-2}$	0.59
4	Buildings at one side, but about continuously built; distance axis-façade smaller than 3 times height of buildings	$5.0 \cdot 10^{-4}$	$-3.2 \cdot 10^{-2}$	0.57

[a] Not assessed in this study

$$Et = \max\left[(34 + 13.3 \cdot \log(V_{t,s})),\right.$$
$$\left.(56 + 0.6 \cdot (0.5 \cdot i - 1.5))\right] \tag{4A}$$

where $V_{c,s}$ is the average car speed in scenario s (km·h^{-1}); i is the road slope (%); and $V_{t,s}$ is the average truck speed in scenario s (km·h^{-1}). The default value for the road slope used in this study is 0%. There are two restrictions regarding the use of Eq. (A2), Eq. (A3) and Eq. (A4): the road surface must be asphalt and the number of vehicles per hour must be the same in both directions [2].

The average sound pressure level drops 3 dB(A) when the distance to the sound source is doubled. Therefore, in order to calculate the noise level during daytime at the façade, **Eq. (A5)** can be used:

$$LAeq_{f,s} = LAeq_{r,s} - 3 \cdot \left({}^{2}\log(S)\right) \tag{5A}$$

where $LAeq_{f,s}$ is the average sound pressure level during daytime at the façade of the house in scenario s (dB(A)). It is assumed that the average sound pressure levels during nighttime are 9 dB(A) lower than the average sound pressure levels during daytime [2].

The lower and upper threshold values of noise levels at the façade of the dwelling for the considered health effects are given in **Table A5** [2]. Changes in response for noise levels that are between these threshold values are characterized by a linear dose-response relationship. It is uncertain whether the linear dose-response relationship for noise is also valid for noise level values above the upper threshold value, but the traffic intensity must be very high to generate noise levels that high.

Table A5: Lower and upper threshold values for noise levels at the façade of the dwelling having indoor health impacts [2]

Human health damage category	Lower threshold value (dB(A))	Upper threshold value (dB(A))
Communication disturbances	55	70
Sleep disturbances	46	61

The threshold values for noise levels at the façade of the dwelling are valid for average conditions. When additional noise reducing measures are taken, the noise levels in the indoor environment will be lower.

Damage factors noise

The disability weights and years living disabled are given in **Table A6**.

Table A6: Disability weights and years living disabled for noise-related human health damage categories [2]

Damage category	DW_k [a] (–)	YLD_k [b] (y)
Communication disturbances	0.033	33
Sleep disturbances	0.055	23

[a] disability weight for human health damage category *k*
[b] years of living disabled for human health damage category *k*

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